Ultrashort Pulse Decomposition in Meander Line with Broad-Side Coupling of Two Turns

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***Abstract* – Ultrashort pulse decomposition into a sequence of pulses of smaller amplitude in meander line with broad-side coupling of two turns is demonstrated. For this purpose, a number of simple conditions, which ensure such decomposition in line with broad-side coupling have been proposed and used. The maximum ultrashort pulse attenuation at the end of the second turn up to 4.8 times with fulfillment of these conditions is shown.**

***Index Terms* – Meander line, two turns, ultrashort pulse, even mode, odd mode**

I. INTRODUCTION

A MODERN HUMAN IS dependent on the correct and uninterrupted operating of electronic technical means (TM) surrounding him in daily life. Therefore, the intentional power electromagnetic interference (IEMI) is a real threat to the modern society. For the first time attention to this threat was paid in the report of Professor V.M. Loborev in 1996 in the plenary session of the AMEREM conference [1]. There are many cases of IEMI on the infrastructure objects of society [2]. For example, in 2012 one of the largest banks in the UK became the object of blackmail by intruders who threatened to remotely disable the entire security system of the bank and its computer equipment with the help of a powerful generator of EM pulses. In the Russian Federation IEMI is mainly considered as a treat to the objects of the fuel and energy complex. The organization and content of work on protection from IEMI are regulated by the system of target standards of the Russian Federation, the main of which is GOST R 56103-14 [3].

Meanwhile, not only the IEMI is danger, but also other effects, such as an electrostatic discharge (ESD), electromagnetic pulse of a nuclear explosion, lightning. The danger of such effects is caused by their short duration (up to hundreds of nanoseconds) and high voltage (up to decades of kilovolts). Because of their similarity to pulsed signals, such effects are also called ultrashort pulses. Such pulses can instantly disable sensitive circuits due to high power. Therefore, an urgent task is to provide protection against ultrashort pulses in the TM design. At the moment, the basic protection against ultrashort pulses composes various nonlinear elements, such as spark gaps, varistors, Zener diodes, etc. [4]. Besides the mentioned devises, other devices are also used, but in some cases they cannot provide appropriate protection due to a number of drawbacks, which make them not applicable [5]. In addition, to ensure uninterrupted operation of the TM, it is necessary to provide the protection in a range of impacts, which is impossible to implement without complicating the system and increasing the number of protection cascades [6, 7]. In practice, simplicity and low cost of protection devices are required. Therefore, it is necessary to study new and simple approaches to the protection of radio electronic equipment against ultrashort pulses.

The protective strip-line devices on a PCB which using may not require a separate device at all are noteworthy. For protection, specially configured stripes already available on the PCB can be used. So, there are many different devices based on strip lines for protection against ultrashort pulses (including ESD protection) and signal filtering in frequency domain [8–12]. Devices based on the phenomenon of modal decomposition of a signal into a sequence of pulses due to the difference of per-unit length delays are worth noticing [11, 12]. The main feature of the devices is the decomposition of the ultrashort pulse into three pulses in the turn of the meander line, in contrast to modal filters. The decomposition of ultrashort pulse in the meander line is achieved by choosing of the line parameters, which is based on providing a number of simple conditions. The possibility of such decomposition in a one turn of meander line in the practice has proved by the full scale experiment results [12]. In continuation of the study, the simulation results of a meander microstrip line of two turns connected in cascade are presented, where the analysis of the results was performed not only with the purpose of analyzing the attenuation of the ultrashort pulse amplitude, but also from the point of view of analog signal processing in order to generate a pulse train from single pulse or to multiply pulses [13]. Meanwhile, lines with a different type of coupling, for example, with a broad-side coupling, where much the largest difference in the per-unit-length delays of the even and odd modes can be provided, are not considered. For this reason, the purpose of this paper is to investigate ultrashort pulse decomposition in the meander line with broad-side coupling of two turns. To achieve this purpose, it is necessary to reveal the conditions ensuring the ultrashort pulse decomposition into a sequence of pulses in the first turn, and then each of them in the

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second turn, to describe each of the main pulses resulted from the ultrashort pulse decomposition after propagation through each of the turns, and to analyze the obtained results.

II. INITIAL DATA FOR SIMULATION

For the investigations meander line with broad-side coupling of two turns connected in cascade is chosen. First and second turns have the same cross-section view, an example of which is presented in Fig. 1. The circuit diagram of the meander line of two turns is shown in Fig. 2. The beginning of the first turn is connected to a signal generator represented in the circuit by an ideal e.m.f. source E and the internal resistance $R1$. The end of the first turn is connected in series with the beginning of the second turn, and the end of the second turn is connected to the receiving device represented in the diagram by the resistance $R2$. To minimize reflections from the line ends, resistance $R1$ is taken equal to the geometric mean of the characteristic impedance of the first turn modes and the resistance $R2$ – of the second turn. The length of the first turn (l_1) is 35 mm, the second (l_2) – 15 mm. As an excitation, a pulse with trapezoidal waveform with e.m.f. amplitude of 1 V, flat top duration of 100 ps, and the rise and fall durations of 50 ps each is used.

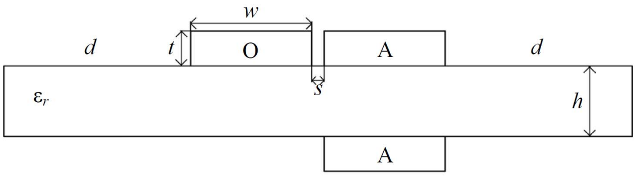

Fig. 1. Cross section of the meander line turns with broad-side coupling

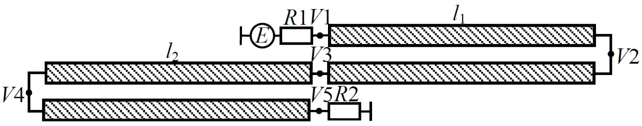

Fig. 2. Circuit diagram of the meander line of two turns

Earlier we revealed that for the complete decomposition of the ultrashort pulse in a meander line of two turns, first we need to decompose the ultrashort pulse in the first turn into three main pulses (cross-talk, odd and even modes), and then, in the second turn, to perform the same decomposition each of these pulses into three pulses [13]. In addition, in the first turn, it is necessary to ensure equal delays between the decomposition pulses in order to exclude the overlapping of the pulses on each other after passing through the second turn. For this aim it is necessary to fulfill the condition in the first turn

$$\tau_{max} \geq 2\tau_{min} \quad (1)$$

where τ_{max} and τ_{min} are the maximum and minimum values of per-unit-length delays of even and odd modes of the line.

To exclude partially the influence of reflections from the junctions of the half-turns (nodes $V2$ and $V4$) and the turns (node $V3$), and also from the beginning and end of the line (nodes $V1$ and $V5$), on the main signal, it is necessary to fulfill another condition, obtained after analyses of a numerous of simulation results

$$\tau_{max} \geq 3\tau_{min}. \quad (2)$$

Also, as a result of the investigation of the meander microstrip line of two turns, it was revealed that for complete decomposition of the ultrashort pulse, exclusion of overlapping of decomposition pulses and minimization of the signal amplitude at the end of the line, it is necessary to provide a number of simple conditions:

$$2l_2\tau_{o2} \geq t_\Sigma, \quad (3)$$

$$2l_2|\tau_{e2} - \tau_{o2}| \geq t_\Sigma, \quad (4)$$

$$2l_1\tau_{o1} - 2l_2\tau_{e2} \geq t_\Sigma, \quad (5)$$

$$2l_1(\tau_{e1} - \tau_{o1}) - 2l_2\tau_{e2} \geq t_\Sigma. \quad (6)$$

where τ_{oi} and τ_{ei} are the per-unit-length delays of even and odd modes of the first (i =1) and the second (i=2) turns, and l_i are their lengths.

Since, in the line with broad-side coupling considered in this paper, the value of per-unit-length delay of odd mode is always beyond of the value of per-unit-length delay of even mode, then conditions (3), (5), (6) should be rewritten as

$$2l_2\tau_{e2} \geq t_\Sigma, \quad (7)$$

$$2l_1\tau_{e1} - 2l_2\tau_{o2} \geq t_\Sigma, \quad (8)$$

$$2l_1(\tau_{o1} - \tau_{e1}) - 2l_2\tau_{o2} \geq t_\Sigma. \quad (9)$$

At the same time, conditions (1) and (2) do not depend on the configuration of the structure and are applicable to the turn of the meander line with any type of coupling.

III. SIMULATION RESULTS

A simulation of a turn of meander line with broad-side coupling of two turns without losses in conductors and dielectric performed in TALGAT software [14]. First, in accordance with the conditions described above, the cross-section parameters of the first and second turns are selected. As a result of parametric optimization according to the criterion for the fulfillment of condition (1) in the first turn, the following parameters of its cross-section were obtained: w_1=1000 µm, t_1=18 µm, h_1=200 µm, s_1=209.5 µm, ε_{r1}=476.3. The calculated matrices of per-unit-length coefficients of electrostatic (**C**) and electromagnetic (**L**) inductions of the first turn were

$$\mathbf{C} = \begin{bmatrix} 23.429 & -22.204 \\ -22.204 & 23.404 \end{bmatrix} \text{nF/m},$$

$$\mathbf{L} = \begin{bmatrix} 486.415 & 400.217 \\ 400.217 & 504.217 \end{bmatrix} \text{nH/m}.$$

Using the corresponding coefficients of the **C** and **L** matrices, the per-unit-length delays of the even and odd modes of the first turn of the line were obtained [15]:

τ_{e1}=32.94 ns/m, τ_{o1}=65.87 ns/m. Thus, the condition (1) is fulfilled (65.87 ns/m=2·32.94 ns/m). For clarity, Fig. 3 shows the voltage waveform at the end of the first turn (in node *V*3) for the circuit from Fig. 2 in fulfilling the condition (1).

From the voltage waveform from Fig. 3 is seen, that the signal at the end of the first turn contains a sequence of three pulses: cross-talk (*P*1), odd (*P*2) and even (*P*3) modes. Also from Fig. 3 we can see strong distortions caused by the numerous reflections from the ends of the line and the junctions of the half-turn and between the turns. It can be seen from the signal waveform that the delay of the odd mode pulse is twice the delay of the even mode pulse, and the maximum amplitude of the signal at the end of the first turn is 0.222 V. Similarly to [13], to decompose each of the pulses from the output of the first turn (Fig. 3) in the second turn, first we need to fulfill the condition (2). According to the optimization results, the following parameters of the second turn cross-section ensuring the fulfillment of condition (2) were obtained: w_2=1000 μm, t_2=45 μm, h_2=272 μm, s_2=2.315 μm, ε_{r2}=149.37. The calculated **C** and **L** matrices of the second turn were:

$$\mathbf{C}=\begin{bmatrix} 6996.25 & -4978.99 \\ -4978.99 & 5724.59 \end{bmatrix} \text{ pF/m},$$

$$\mathbf{L}=\begin{bmatrix} 51.802 & 38.213 \\ 38.213 & 243.25 \end{bmatrix} \text{ nH/m}.$$

Using the corresponding coefficients of the **C** and **L** matrices, the per-unit length delays of the even and odd modes of the second turn of the line were obtained: τ_{e2}=11.72 ns/m, τ_{o2}=35.17 ns/m. Thus, the condition (2) is fulfilled (35.17 ns/m=3·11.72 ns/m). We need to note that the parameters of the cross-sections of the first and second turns are also chosen by optimization to ensure conditions (3), and (7)–(9). So, after the substituting of known values of the variables in (3), we get 0.7 ns ≥ 0.2 ns, in (7) – 0.35 ns ≥ 0.2 ns, in (8) – 1.26 ns ≥ 0.2 ns, in (9) – 1.25 ns ≥ 0.2 ns. Thus, the conditions (3) and (7)–(9) are fulfilled. The waveform at the end of the meander line with broad-side coupling of two turns with optimal cross-section parameters, where condition (1) in the first turn and condition (2) in the second, and also conditions (3) and (7)–(9) in the first and second turns were fulfilled, is presented in Fig. 4.

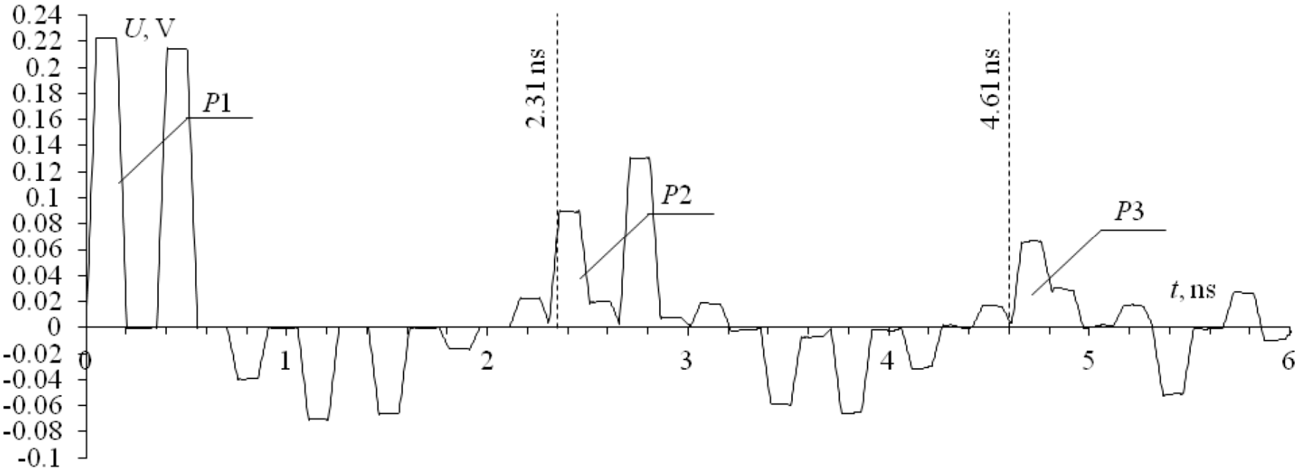

Fig. 3. Voltage waveform at the end of the first turn (in node *V*3) of meander line with broad-side coupling of two turns for condition (1)

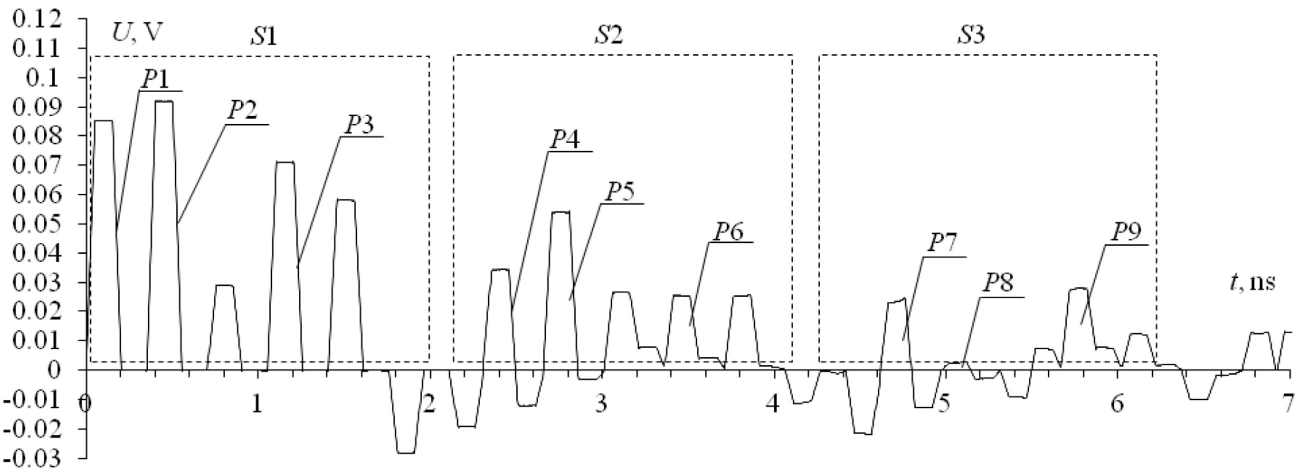

Fig. 4. Voltage waveform an the end of meander line with broad-side coupling of two turns with optimal parameters of the turns

It is seen from Fig. 4, that the ultrashort pulse at the end of meander line with broad-side coupling of two turns is represented by a sequence of many pulses of smaller amplitude, which is not exceeding 92 mV. The first pulse sequence (*S*1) is the result of the decomposition of the cross-talk pulse from the first turn (*P*1 in Fig. 3) in the second turn, which induced from node *V*1 to node *V*3. The second pulse sequence (*S*2) is the result of the decomposition of the even mode pulse from the first turn (*P*2 in Fig. 3) in the second turn. The third pulse sequence (*S*3) represents the result of the decomposition of the odd mode pulse from the first turn (*P*3 in Fig. 3) in the second turn. (Pulse *P*1 is the cross-talk at the end of the line (node *V*5) from the cross-talk pulse induced from node *V*1 to node *V*3 and then at node *V*5, and *P*2 and *P*3 are the even and odd modes of the second turn from the cross-talk pulse at node *V*3. Pulse *P*4 is a cross-talk at node *V*5 from an even mode pulse coming from the first turn (*P*2 in Fig. 3) to node *V*3, pulses *P*5 and *P*6 are even and odd mode pulses from an even mode pulse coming from the first turn to the second. Pulse P7 is a cross-talk at node *V*5 from an odd mode pulse coming from the first turn (*P*3 in Fig. 3) to node *V*3, and *P*8 and *P*9 are even and odd mode pulses from an odd mode pulse coming from the first turn to the second.) Also from Fig. 4, it can be seen that in the line there are many different polarity reflected pulses that distorted the signal waveform and do not allow providing equal amplitude each of pulses of all sequence. As a result, we obtained maximal attenuation of the ultrashort pulse at the end of the meander line with broad-side coupling of two turns up to 4.8 times. Non-fulfillment of any condition leads to uncontrolled distortions of signal waveform at the end of meander line and to increasing of total amplitude of output signal. Distortions caused by the overlapping of the main decomposition pulses against each other (superposition of these pulses). In the future, it is advisable to perform simulation with taking into account of losses in conductors and dielectric, and also simulation with cross-section geometric and electrical parameters corresponding to the real capabilities of manufacturers of modern PCBs.

IV. Conclusion

The decomposition of the defined ultrashort pulse into a sequence of pulses of smaller amplitude in a meander line with broad-side coupling of two turns is demonstrated. For this purpose, a number of conditions have been proposed and used to ensure such decomposition. It is noteworthy that the main conditions are similar to conditions for a meander microstrip line. The remaining conditions are adapted for the line with the broad-side coupling. The main conditions make it possible to ensure the successive arriving of pulses after each turn one after another without overlapping, with the required delay of each of the pulses. The remaining conditions ensure the decomposition of each of the pulses of the sequence from the output of the first turn in the second turn, and also make it possible to exclude the overlapping of even mode pulses from each sequence on the cross-talk pulse of the next sequence. When these conditions are fulfilled, the maximum attenuation of the ultrashort pulse at the end of the second turn is 4.8 times.

We need to note that all the chosen parameters of the line are difficult to implement in practice. Meanwhile, it is possible to achieve these conditions by selecting of the other parameters of lines (for example, the length of each turn) or changing the configuration of the turn cross-section. Finally, we note that the results obtained in this paper allow us to assert that the fulfillment of a number of simple analytical conditions in a meander line with broad-side coupling of two turns allows providing the ultrashort pulse decomposition into a sequence of nine main pulses and to minimize the amplitude of the output signal.

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